

# Automated Inspection of Intaglio Plate Measurement for U.S. Currency

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## ABSTRACT

The United States Bureau of Engraving and Printing (BEP) is tasked with the function of producing billions of banknotes each year to be used by the general public throughout the world. Individual notes must maintain uniform consistency for both security features and print quality. The quality control process necessary to assure the uniform nature of United States currency requires a significant multi-tiered approach. Based on innovative opto-electronic techniques, individual security features are examined as a critical element during each phase of the production process. Print quality standards must also be strictly maintained and monitored to assure the uniformity of the most popular printed item in the world. This presentation describes the approach and some of the techniques developed and implemented within the BEP to carry out the necessary monitoring and control of the quality of intaglio currency printing plates.

**Keywords:** Registration, Inspection, Machine Vision, Plate Measurement Device (PMD)

## 1. INTRODUCTION

The Vision of the Bureau of Engraving and Printing (BEP) is to be “a world class securities printer providing the public and our customer agencies superior products through excellence in manufacturing and technological innovation.” In support of these goals, BEP created a machine to inspect US currency plates. This Plate Measurement Device (PMD) employs state-of-the-art positioning technology and machine vision to automatically measure the layout pattern of engraved images on intaglio plates used in printing United States currency. The uniformity of these plates is paramount to the consistency of this printed security item. This device was designed to recognize inconsistencies associated with the physical note size and location of the engraved images on our printing plates. Accuracy of the plates is vital to print registration which is a critical element associated with validation / authentication detection devices as well as reference standards, commonality and print quality for machine reading of security features.

## 2. CURRENCY PLATE REGISTRATION DATA COLLECTION

BEP developed this printing plate examination device through implementing innovative opto-electronic features. A customized vision system to inspect the uniformity of currency plates was developed. All of the hardware and software components integrated in this specialized system are “off the shelf”. Each of these items can be acquired easily and replaced in the event of component failure.

### 2.1 Fabrication

The transport bed of the PMD models a single segment of an intaglio printing press cylinder. The intricate fabrication process for creating this model segment was carried out in the BEP machine shop. The use of

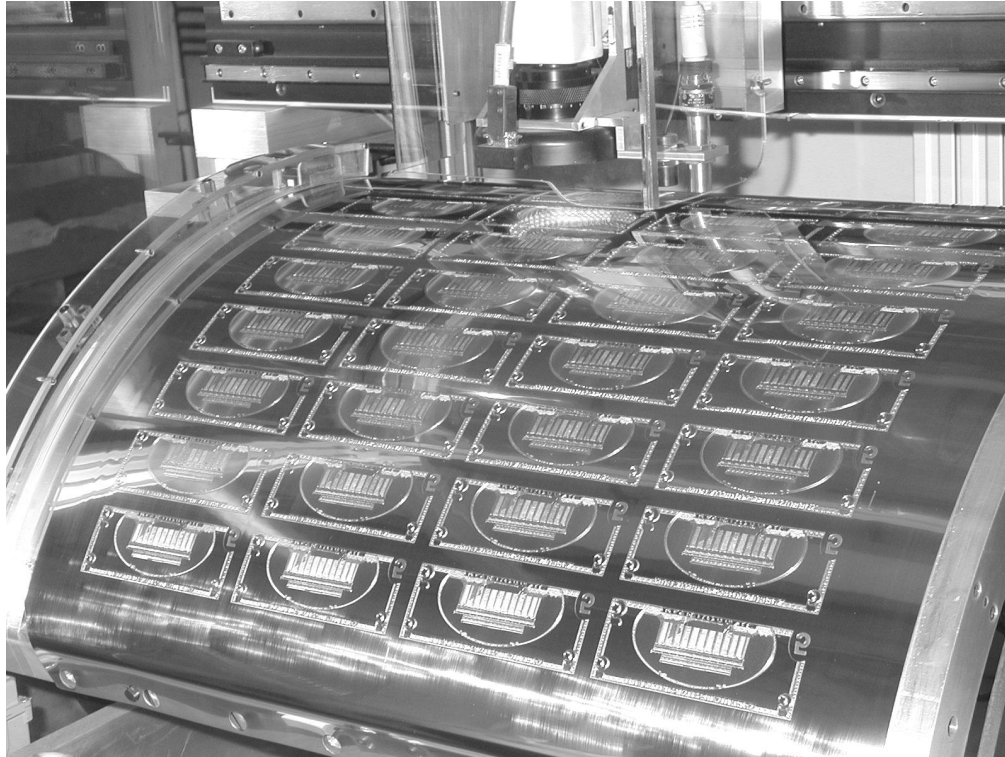


Figure 1. Press Cylinder Model

automated computerized numerical control (CNC) machines and specialized computer aided design / computer aided machining (CAD/CAM) manufacturing software were employed for this project. Utilizing standard computer assisted design tools, BEP machinists created a computerized representation of the device. Enhanced computer modeling software allowed for in-depth analysis, theoretical testing, and design modifications prior to the next value added process. Upon completion of the design analysis, intricate tool path geometry was generated for the fabrication phase of this project. Multi-axis computerized machining centers were utilized to complete the meticulous machining required for the precision operation of this device. Above, Figure 1 shows the completed press cylinder model with a currency plate mounted.

The operator interface of this device was specifically designed and customized to serve the specific task of being “user-friendly”. The intricate and sophisticated operations associated with this 3-axis machine vision system called for limited operator interaction and ease of use.

The X-axis traverses the inspection equipment parallel to the currency plate in a horizontal direction. The theta-axis controls the radial movement of the press cylinder model. The Z-axis traverses the inspection equipment perpendicular to the currency plate to keep the camera a precise distance from the inspection region, this is to compensate for variations in plate thickness and slight mounting inaccuracies.

The PMD was designed and constructed to be portable and easily maneuvered through a standard 36 inch double doorway. The system for mounting currency plates requires minimal force from the operator and no tools.



Figure 2. PMD System

Pneumatic cylinders supply the force to pull the nickel / chrome plate tight against the 18.82" radius cylinder. A plexiglass shroud surrounds the PMD. Safety sensors prevent all motion energy when the doors are open. A pneumatically actuated mechanical lock is engaged during plate removal and installation, for the safety of the operator. Figure 2 shows the complete PMD system including the PMD cylinder, the plexiglass cover and the computerized control counsel.

## 2.2 Machine Vision Inspection System

A 1K x 1K monochrome, area array-camera was used for this application. A measurement tolerance of +/- 0.001" was achieved by using a precision lens with a 0.5" field of view. The PMD inspection software employs eight software calipers to evaluate each engraved note location. A frame-grabber board, integrated within the host computer, captures images from a camera for analysis by the personnel computer (PC). This board also provides digital Input/Output (I/O). The I/O is used to monitor manual switch settings and the state of the safety sensors.

The challenge of capturing a high quality image of the engraving on a polished chrome plate, which is bent on a radius, was solved by the use of a specialized illumination device. A light emitting diode (LED) based, dark field illuminator was chosen for this application because of the unit's accuracy and lifecycle. By illuminating the plate in this manner, the engraving appears clear and defined for the software calipers to perform measurement functions with minimal preprocessing of the image.

The image analysis is performed by commercially available machine vision software. The high precision machine vision software package works with off-the-shelf hardware to meet industrial inspection requirements. The machine vision software control was seamlessly integrated with a Visual Basic User Interface. Specific functions associated with the image analysis operations include edge finding and caliper measurement.

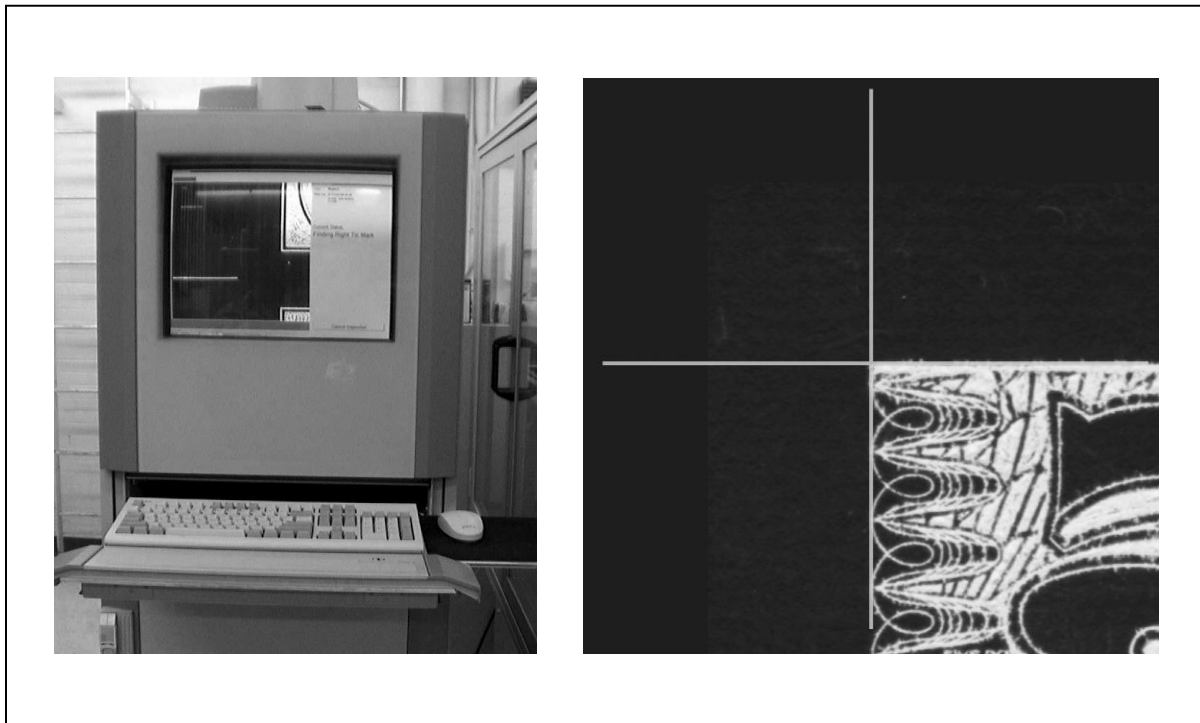


Figure 3. Operator Interface (left), Currency Plate Digital Image (right)

### 2.3 Automation of the PMD

The operator controls this automated machine vision system through the use of a customized, user-friendly, graphical interface, via keyboard and mouse. A 21" color monitor displays a live image of the currency plate being inspected. Figure 3 shows the operator interface as well as a detailed digital image of a currency plate.

A significant number of components operate from the x-axis assembly. The camera, light source, Z-axis, and height sensor are shuttled on the x-axis. The motor used to drive this assembly is a precision, brushless, ironless, three-phase, linear servomotor. Linear motors have become a very important component of precision positioning systems, with numerous advantages over traditional mechanical actuators. The x-axis linear servomotor consists of a fixed permanent magnet track assembly and a moving coil assembly. The shuttle stage design uses recirculating bearings to minimize the overall moving envelope. A linear encoder with a resolution of 0.5 micron (0.000019") is used for the position feedback.

The theta-axis controls radial movement of the press cylinder model. Radial motion is derived from a direct-drive, rotary motor with an internal resolver encoder. The encoder provides feedback to a digital amplifier. A surface-mount, linear encoder is affixed to the cylinder model radius for tuning and positioning of the theta-axis. The surface-mount linear encoder resolution is 1 micron (0.000039"). Two challenging issues resulted from applying a radial servo for this axis, load inertia effects on the motor and compliance of the driven structure. During initial testing of this device, violent drive instability was the consequence. The effects from inertia were caused by a mismatch in the motor inertia and the load inertia, adding ballast to the motor rotor solved this problem. The load compliance issue was addressed by additional gusseting of the press cylinder model. These two improvements yielded drive stability and the desired 1-micron accuracy of the theta-axis.

The Z-axis traverses the camera and light source perpendicular to the currency plate. This axis maintains a precise distance between the camera and the plate surface. It is necessary to compensate for variations in plate thickness and slight mounting inaccuracies. The Z-axis drive is a center-driven, lead-screw motor. The resolution of the encoder is 5 microns (0.000195"). A displacement sensor, which was chosen for its accuracy, provides positioning feedback over engraved areas.

## **Plate Data \$20 Front 472-46-46**

User: James Hess

Data recorded on: Thursday, Apr 26 2001 01:37:14 PM

Hi:0.0289 Lo:0.0292

Layout Dimensions: 623.881 width 529.057 height

Average Note Dimensions (trim edge to trim edge): 155.970 width 66.132 height

Average Note Dimensions (print edge to print edge): 147.887 width 59.119 height

Features Shown: (Step and Repeat)

All measurements in millimeters

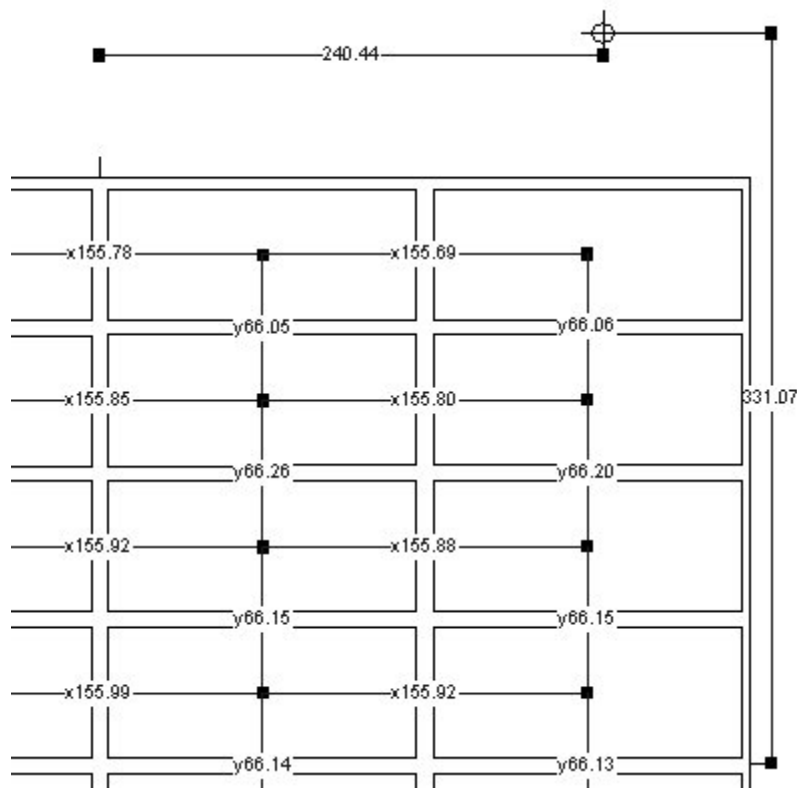


Figure 4. Step and Repeat Measurements.

A PC-based, three-axis, servo controller is used for the positioning of the servomotors. The controller's on board 32-bit microprocessor implements a digital integrator, proportional, and derivative gain (PID) filter with 4 kHz update rate. It handles all trajectory generation and interpolation functions. The controller eliminates jerk by programmable acceleration and deceleration with profile smoothing. Additionally, this controller provides a hardware interrupt line that will, when enabled, interrupt the PC for events such as motion completion or excess position error. This board provides for analog and digital I/O. The I/O is used for operator safety, end of travel limits and component faults.

In order to orient the PMD, a drive initialization sequence is implemented. The drive initialization sequence positions each servomotor to a "home position" (mechanical reference point). When the "home position" has been

## **Plate Comparison Data**

Comparing Plates: \$20 Front 472-39-39 to \$20 Front 472-46-46

X tolerance: .06

Y tolerance: .06

Features Compared: (Step and Repeat)

All measurements in millimeters

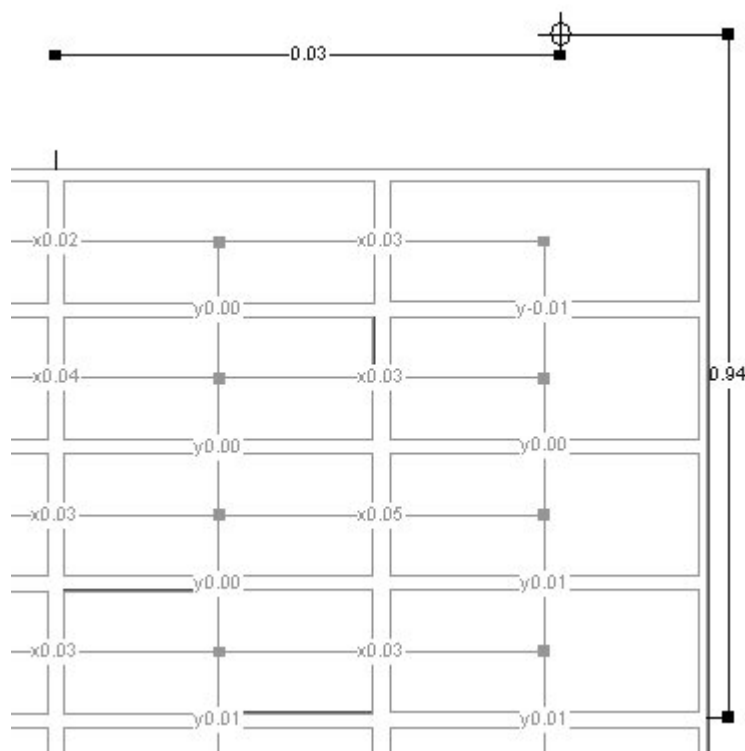


Figure 5. Step and Repeat Measurements Compared To Golden Image.

reached, a transition in the state of the home input alerts the controller that a particular reference point has been reached. The controller then resets the digital position of the axis to reflect the mechanical reference point. The home location sensors are non-contact limit switch "Hall-Effect" sensors. A "Hall-Effect" sensor detects the proximity of a magnet and provides a discrete output to assure an accurate position reference. Reference point sensor repeatability is a critical element for data standardization; these sensors are accurate to within +/- 2 microns (0.000078 inches).

## Note Measurement Report

### Center of Intaglio by Note, Old Step

distance from center substrate to center of intaglio, mm

|        |                |         |         |            | BACK  | FACE  |
|--------|----------------|---------|---------|------------|-------|-------|
| NOTES: | 100            | GRID X: | 0.25 mm | $\sigma_x$ | 0.529 | 0.515 |
| DENOM: | \$5            | GRID Y: | 0.25 mm | $\sigma_y$ | 1.064 | 0.848 |
| SIDE:  | Front and Back |         |         |            |       |       |



Center of Face Intaglio



Center of back Intaglio

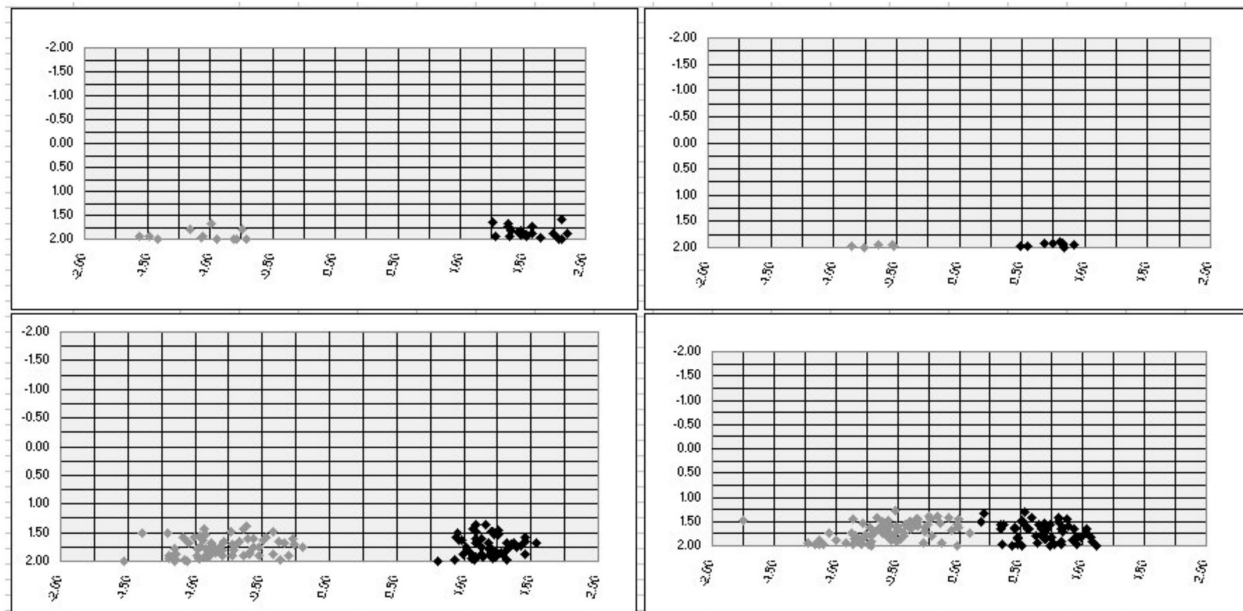


Figure 6. Old Step Layout data

### 3. DATA ANALYSIS

Data analysis is performed after the PMD captures all pertinent plate information. Pixel data and three axis position coordinates are computed and scaled to provide the following: step and repeat data (figure 4); note corner measurement data; and note center measurement data. In order to minimize information overload at the user interface, only one of the data sets can be displayed at a time. All of the data is automatically saved to a network database. The analysis tool can also compare the current plate to a “Golden Plate” (figure 5). The “Golden” can either be a mathematical composite of the target plate, or a plate that has been previously measured. When comparing the current plate to the “Golden”, the operator may specify a tolerance. The monitor displays measurements outside the tolerance in red and the acceptable reading in green.

The Golden comparison provides the operator with immediate “Go/No-Go” feedback, while the networked database is used offline to detect process trends. Spreadsheets are used to isolate the many variables associated with plate manufacturing. In the following two examples (figures 6 and 7), the center of each graph represents the intended center of each note on a currency plate. Each polygon on the graph represents the center of notes from measured plates. Figure 6 is a graph of the position of four (32 notes per plate) of the note centers for a redesigned, five-dollar, faceplate (enlarged portrait). Figure 7 is a graph of the position of the same four note centers after the first layout change. This

## Note Measurement Report

### Center of Intaglio by Note, New Step

distance from center substrate to center of intaglio, mm

|        |                |         |         |            |  | BACK  | FACE  |
|--------|----------------|---------|---------|------------|--|-------|-------|
| NOTES: | 100            | GRID X: | 0.25 mm | $\sigma_x$ |  | 0.366 | 0.497 |
| DENOM: | \$5            | GRID Y: | 0.25 mm | $\sigma_y$ |  | 0.305 | 0.339 |
| SIDE:  | Front and Back |         |         |            |  |       |       |



Center of Face Intaglio



Center of back Intaglio

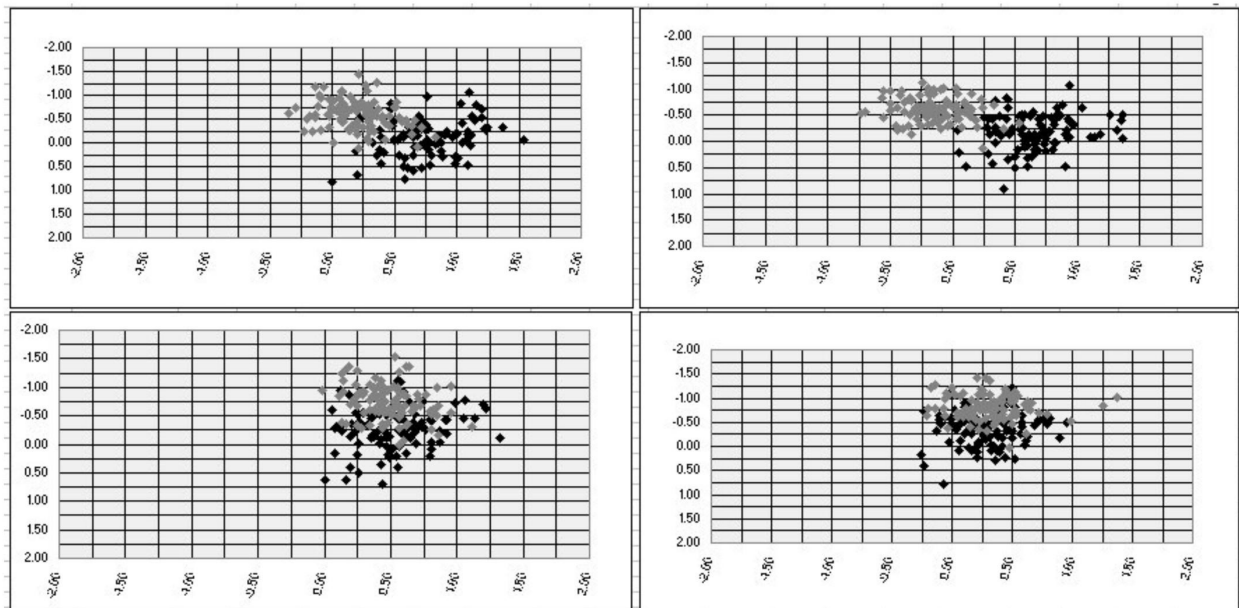


Figure 7. New Step Layout data

data is being factored into the next layout change. The target is to achieve the best registration possible with an variable process.

## 4. CONCLUSION

This prototype plate-measuring device is in daily use at the BEP as a quality measure. This system is proving to be an integral part of the quality assurance and process control associated with the printing of United States currency. The implementation of this inspection system will have significant long-range effects on the use of United States currency as it relates to the consistency of machine-readable features. The PMD data will be instrumental in implementing any future security or design changes.

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